Stellar graveyards in AGN disks

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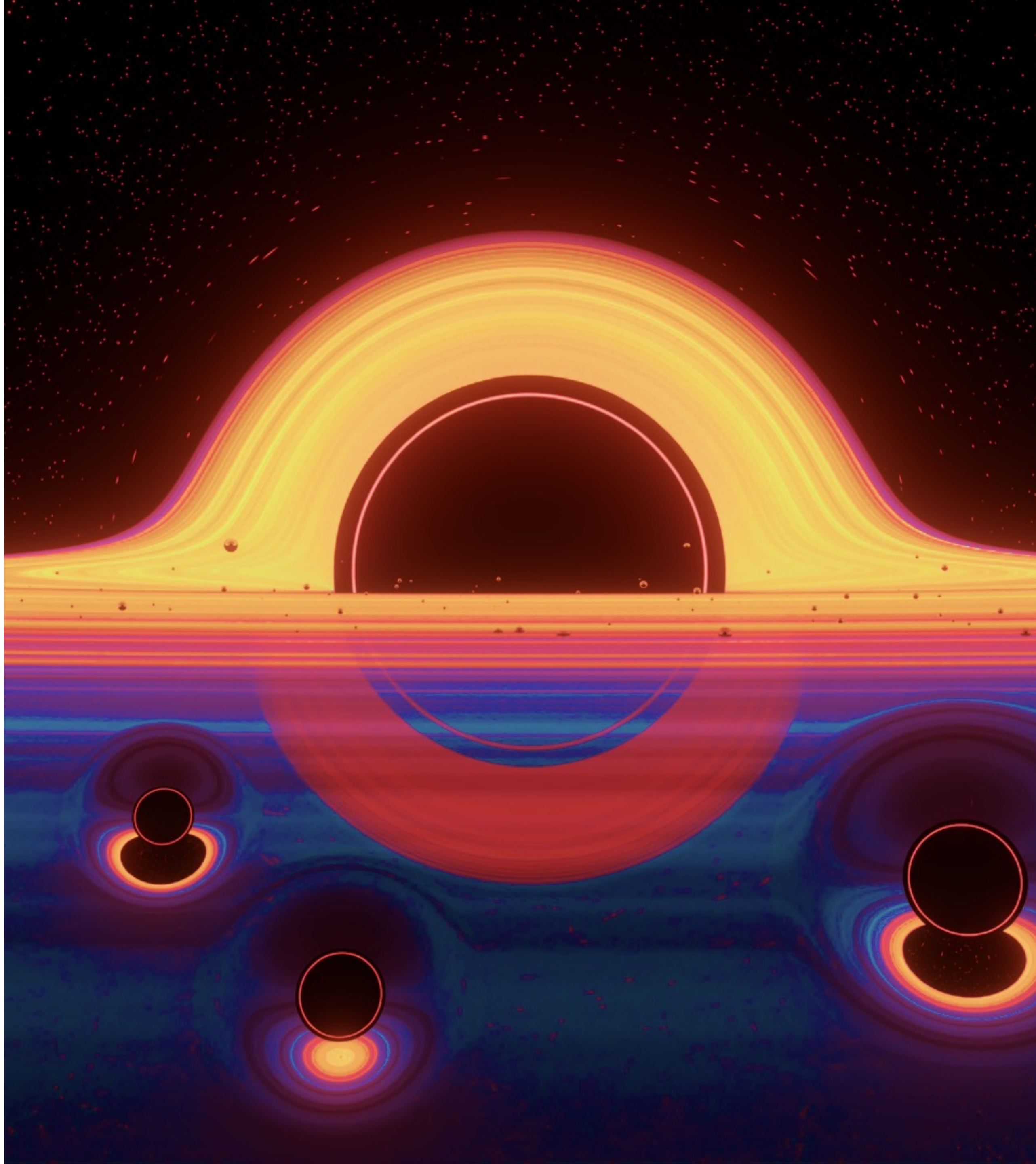
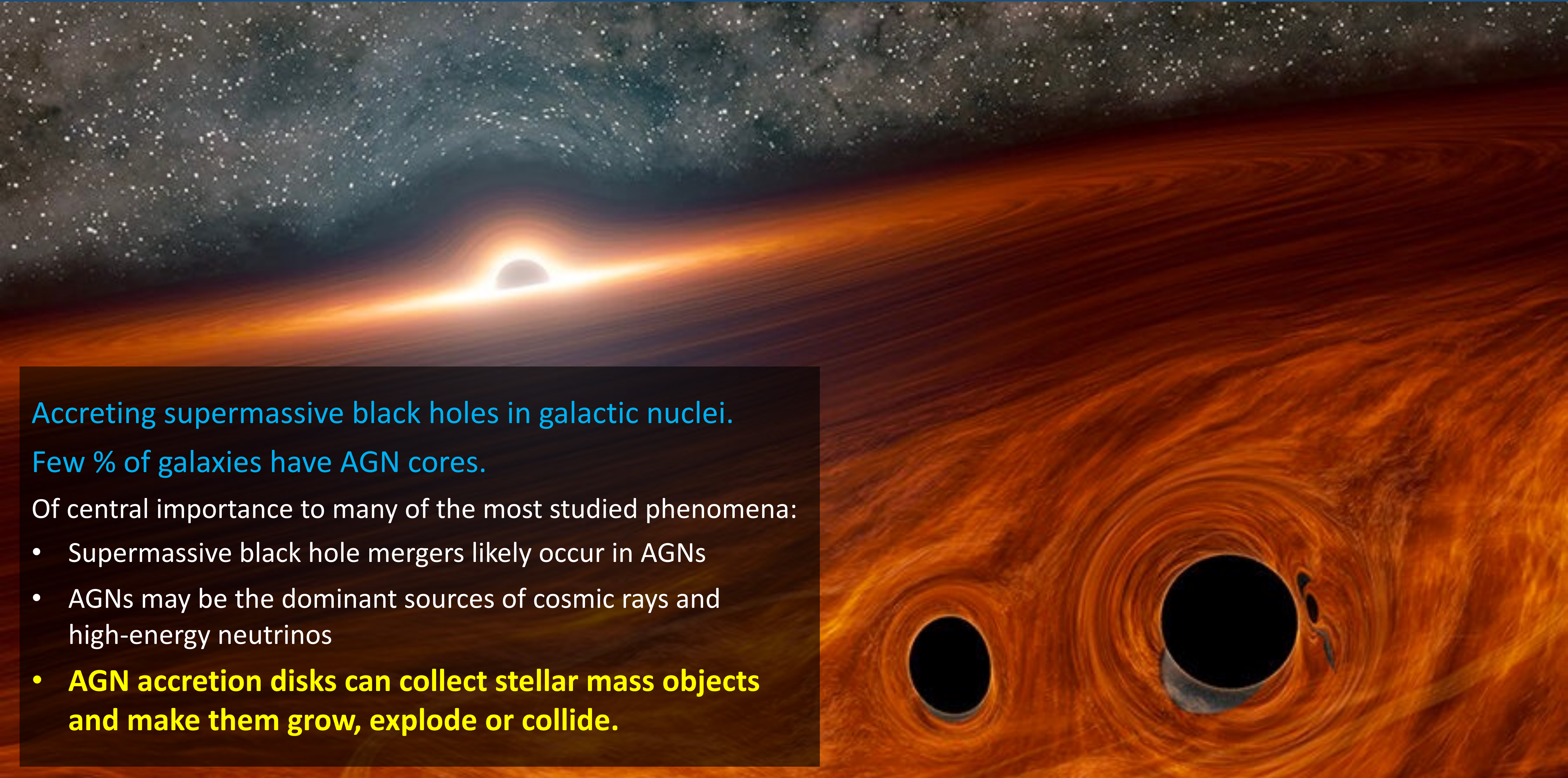


Active Galactic Nuclei



Accreting supermassive black holes in galactic nuclei.

Few % of galaxies have AGN cores.

Of central importance to many of the most studied phenomena:

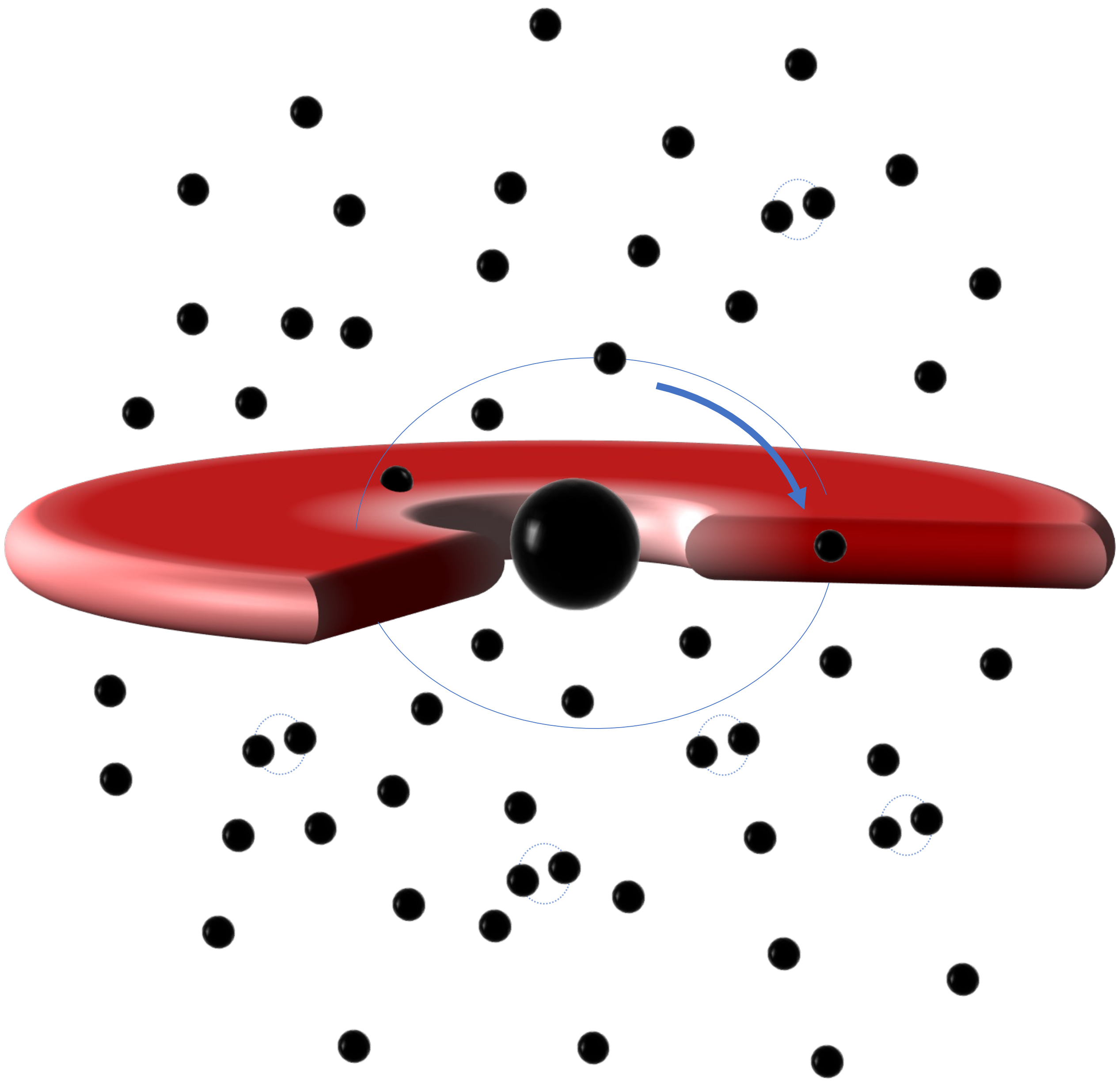
- Supermassive black hole mergers likely occur in AGNs
- AGNs may be the dominant sources of cosmic rays and high-energy neutrinos
- **AGN accretion disks can collect stellar mass objects and make them grow, explode or collide.**

Why are there stellar objects in AGN disks?

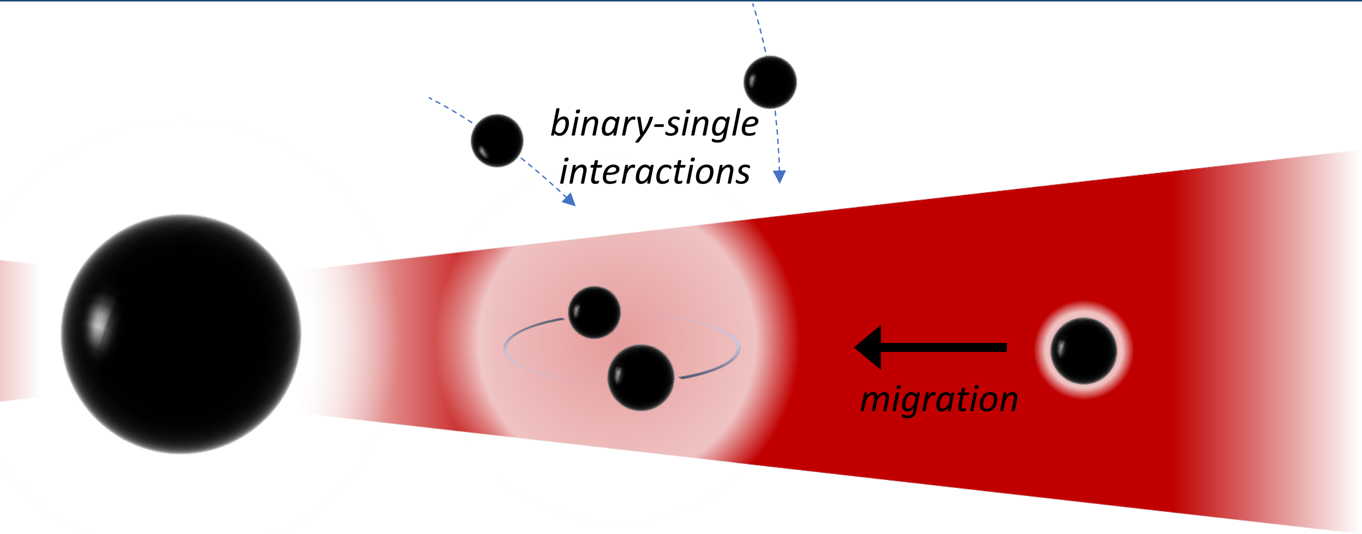
1. **Star formation within the disk.**
    - Stars form due to gravitational clumping.
    - After stellar evolution – leave black holes or neutron stars in disk.

2. **Disk capture.**
    - Mass segregation – heavier objects move closer to the center
      - *observed near Sgr A* (Hailey+ 2018).*
    - Periodic disk crossing: – some stellar objects align their orbit with disk plane (Bartos+ 2017).

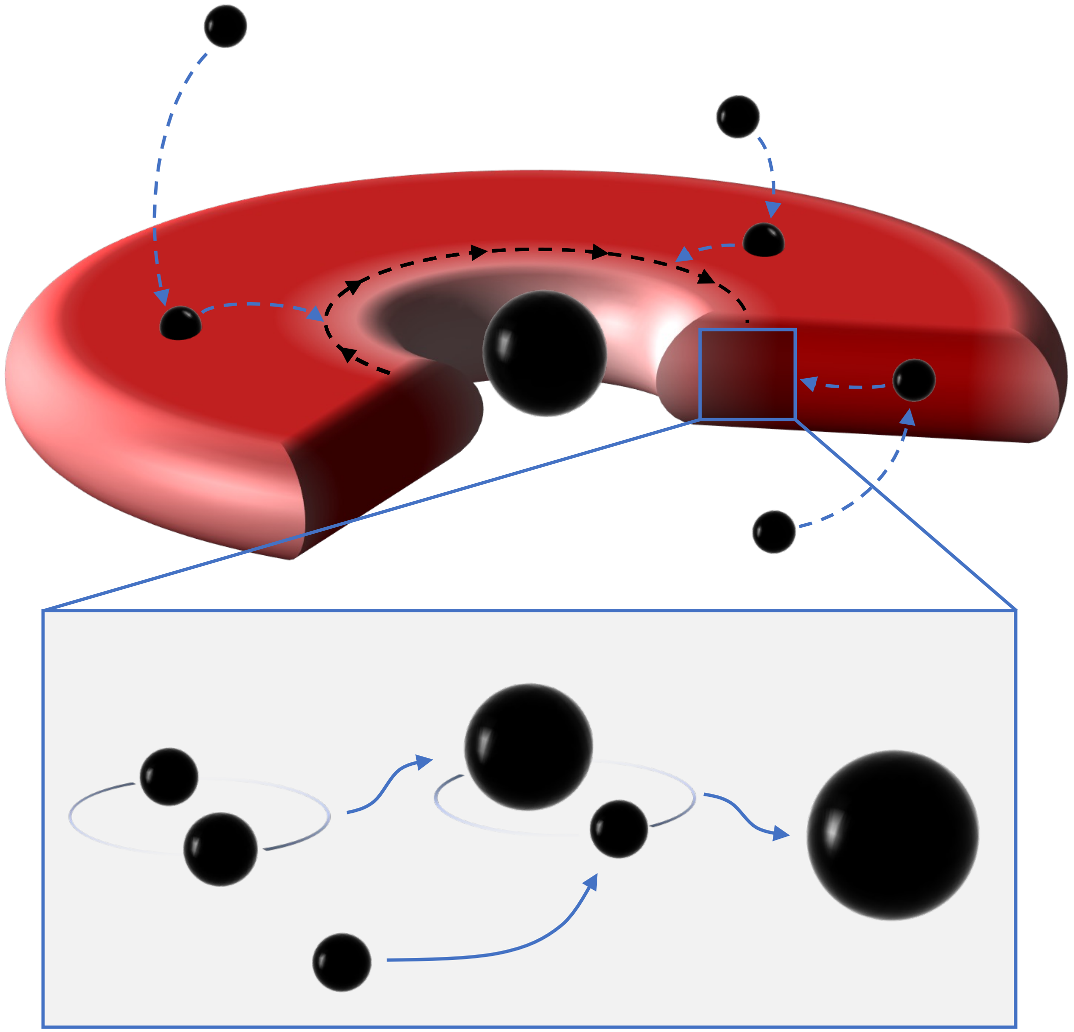
There can be several black holes, neutron stars and stars residing within an AGN disk.



What happens to black holes in the disk?



1. Migration inwards due to pressure gradient.
    - *Migration trap at few hundred R_S?*
    - *Interaction with stars/BHs in center -* $\sim 10^{-2} pc.$
2. Gas capture – efficient binary formation in gas.
3. Rapid inspiral:
    a. Dynamical friction in gas.
    b. Binary-single interactions with stellar objects outside the disk.
4. Remnant stays in/near disk → can merge with another black hole → hierarchical mergers.



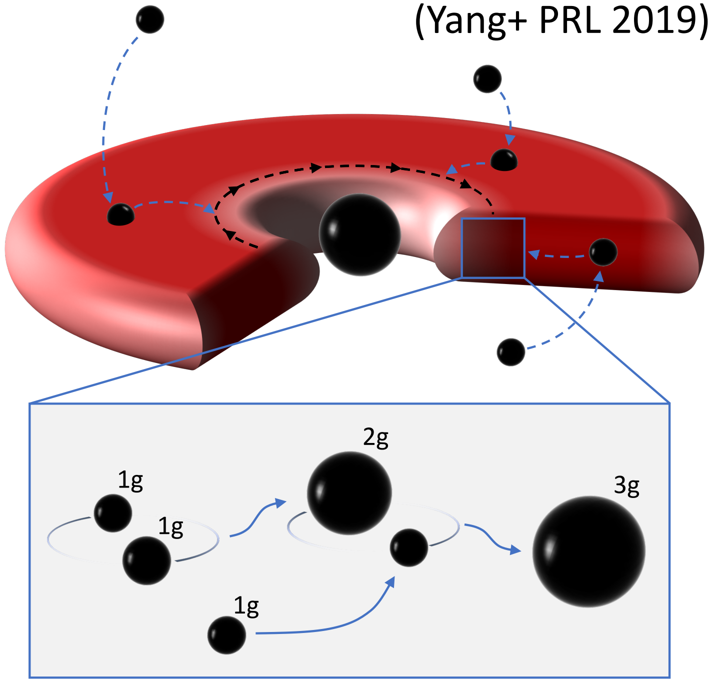
Observational consequences

Higher mass

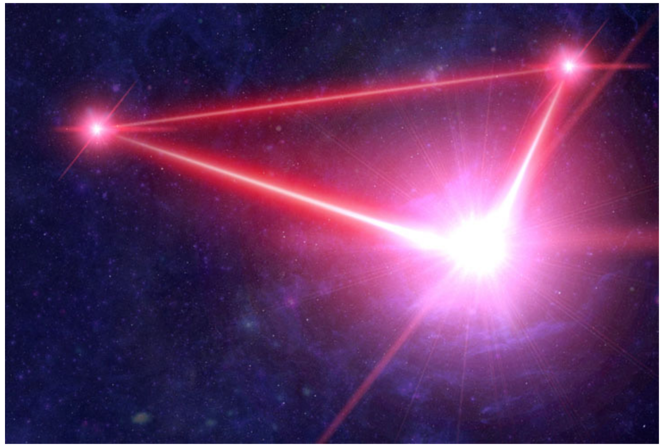
Mass segregation
Heavier objects in galactic center migrate inward, lighter ones move out.
(O'Leary+ 2009)

Accretion
Black holes (and neutron stars) accrete gas inside the AGN disk.
(Yang+ ApJ Lett 2019)

Hierarchical mergers.
Multiple black holes can migrate to same place and merge consecutively.
(Yang+ PRL 2019)



LISA
Consecutive mergers can create intermediate mass black holes ($> 100M_\odot$)
→ Merger with supermassive black hole (or stellar-mass black hole): interesting gravitational wave source for LISA.



Higher spin

Both accretion and mergers can increase spin.

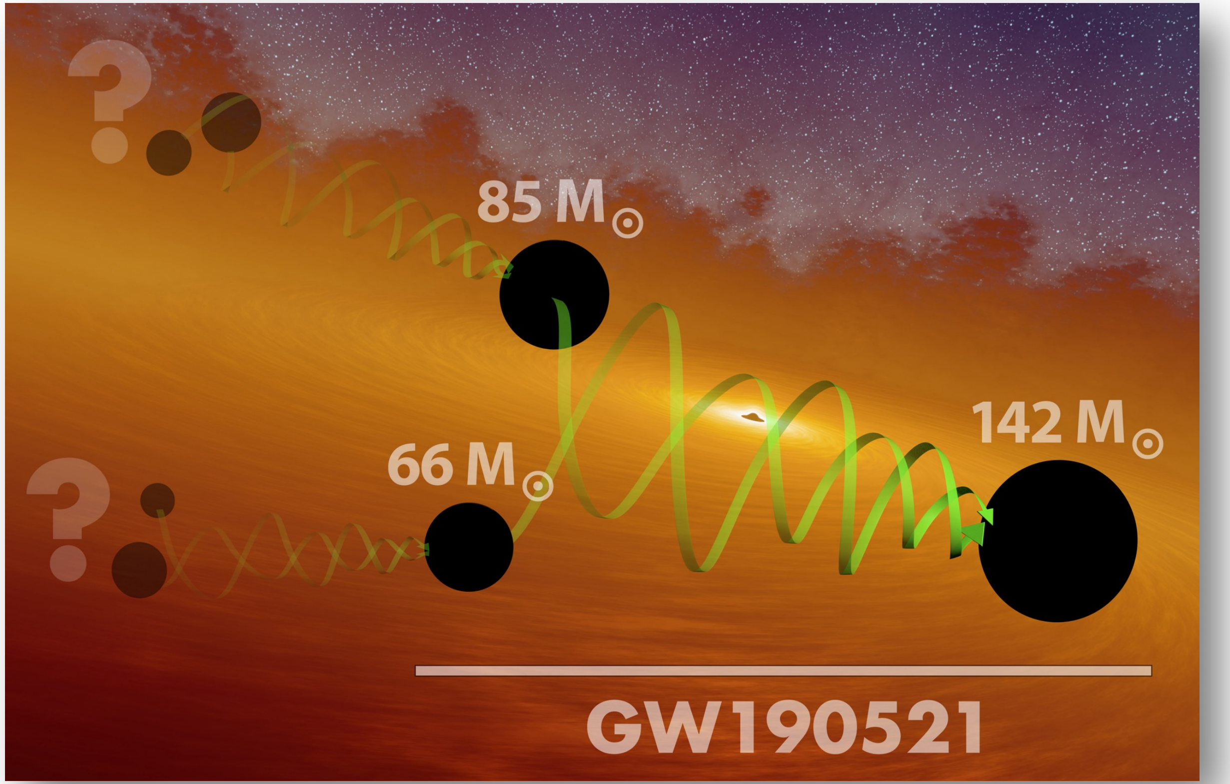
The black hole that shouldn't exist: GW190521

- $\boldsymbol{M_1 > 65 M_\odot}$: Mass of heavier black hole is difficult to explain with stellar evolution, although uncertainties remain.

  Possible explanation: the black holes are the
  remnants of previous mergers?

- **High spin:** higher than other black hole mergers observed so far. Could have increased through previous mergers or accretion.

- **Misaligned spin from orbit:** also difficult to explain with stellar binaries where spin should be parallel with binary orbit. It is expected if binaries form in chance encounters (such as the case for multiple mergers).



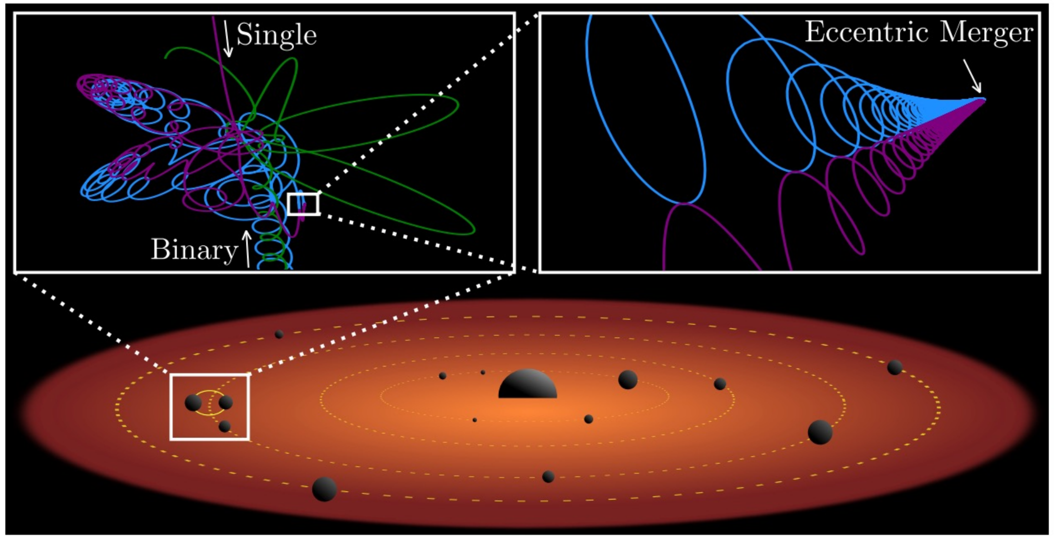
+1 observational consequence: eccentricity

- Gravitational waves circularize the binary orbit → orbital eccentricity is expected only if: (1) binary recently formed or (2) external source supplies eccentricity.

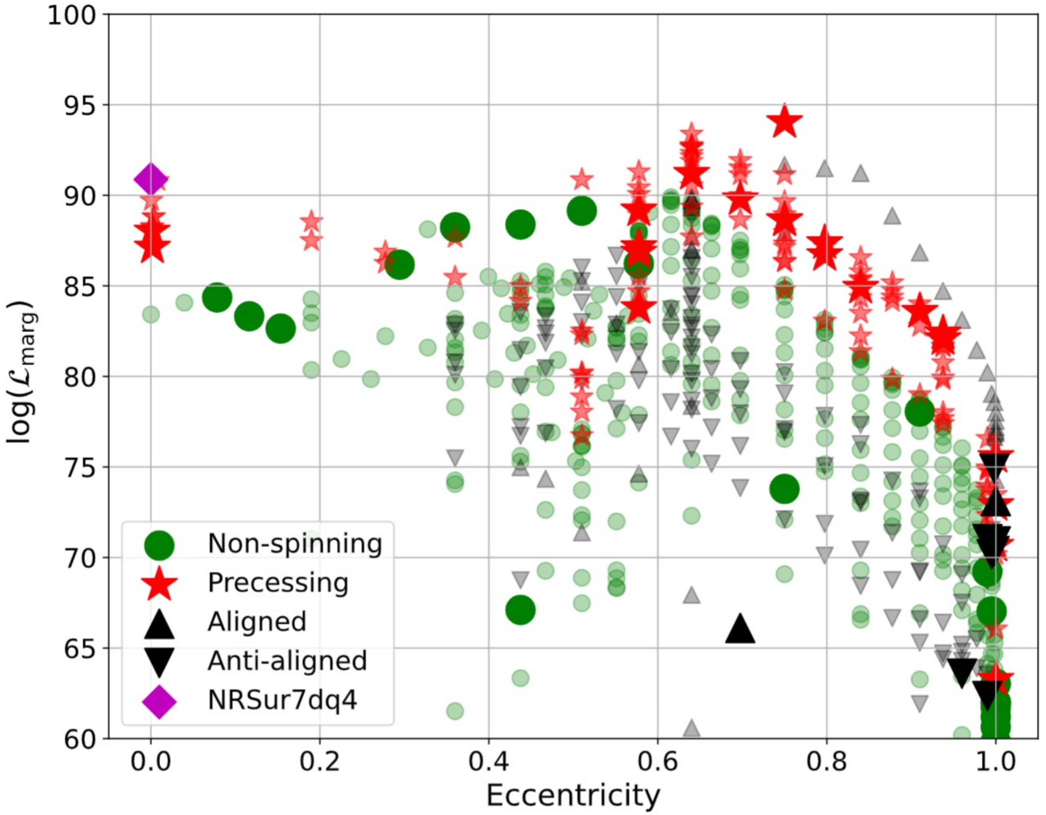
- AGNs could be best sites for high eccentricity mergers. 2D interactions lead to high eccentricity much more often than 3D interactions. (Samsing+ Nature 2022).

- Using a large suite of numerical relativity simulations, we found that GW190521 is most consistent with highly eccentric binary with $e \approx 0.7$. (Gayathri+ Nature Astronomy 2022).
- Using semi-analytic template banks gives similar results (Romero-Shaw 2020, Gamba+ 2021).

- GW190521 is first identified highly eccentric binary.



Samsing+ Nature 2022



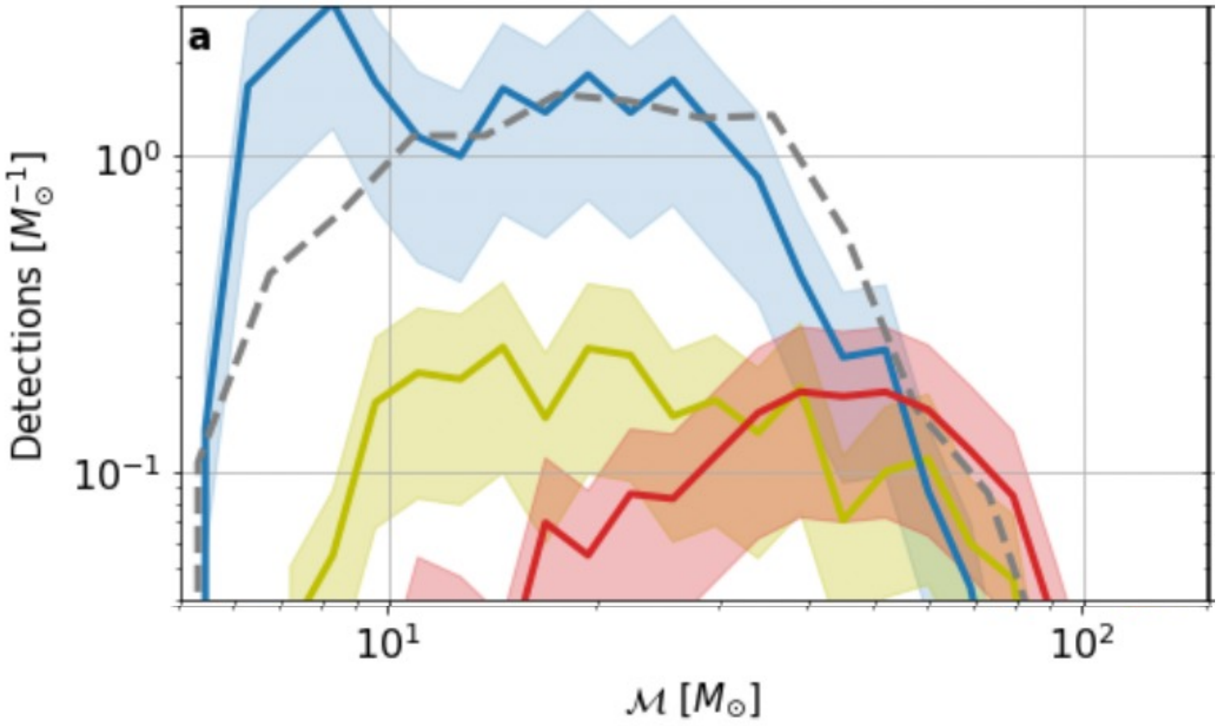
Gayathri+ Nature Astronomy 2022

What fraction of gravitational waves are from AGNs?

Gayathri+ ApJ Lett 2021

Model comparison

- Compare AGN model vs overall mass+spin fit to all LIGO-Virgo events.
- Determine for each event whether overall mass+spin fit or AGN model works better.
- High-mass ($M_{chirp} > 40\ M_{\odot}$): overwhelmingly of AGN origin
- **20% of LIGO-Virgo detections could come from AGNs**

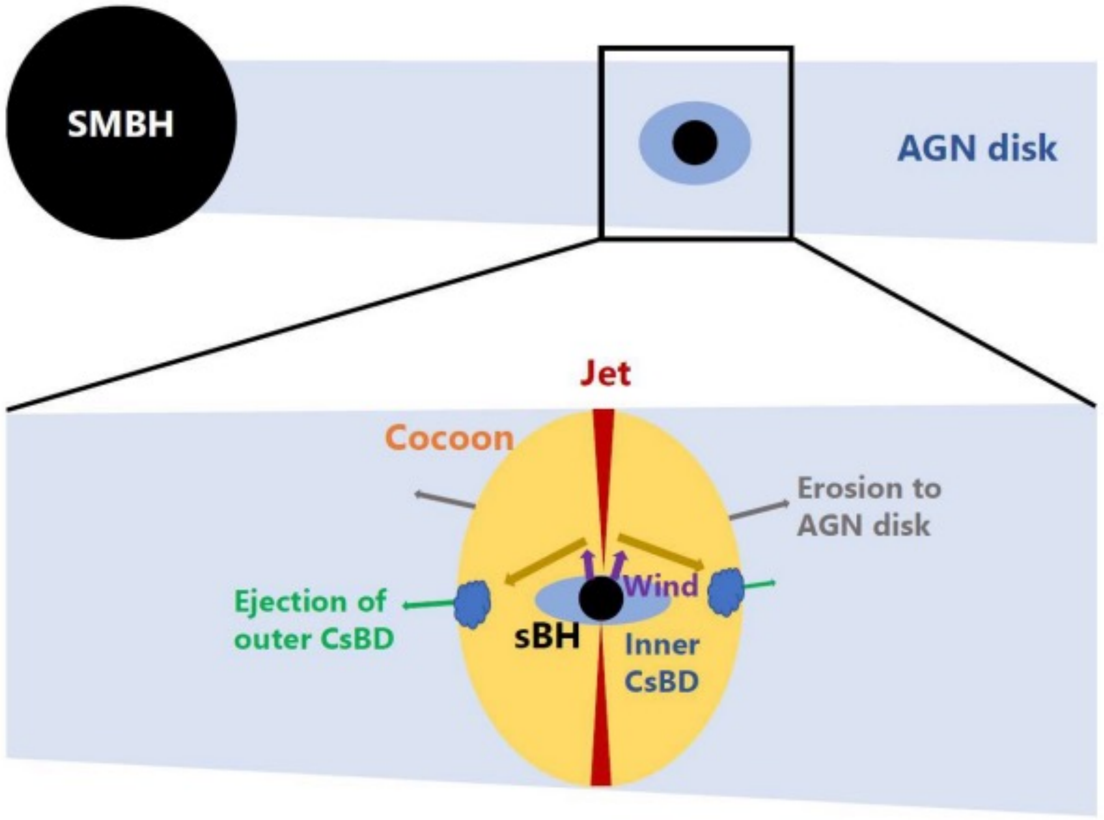


- fit on LIGO/Virgo detections

- fit on LIGO/Virgo detections

High accretion and effect on AGN disk

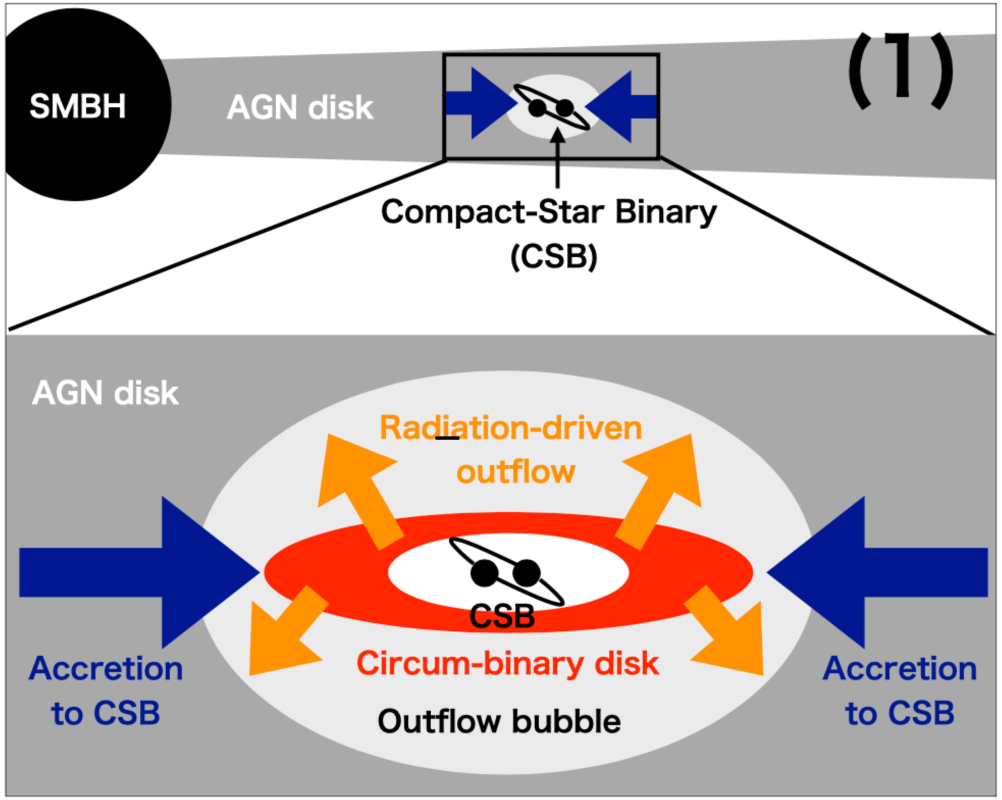
- High gas density within disk
  → black holes could rapidly grow through accretion.
  → intermediate mass black holes?
- Would deplete AGN disk – inconsistent with observations.
- Rapidly accreting black holes can launch winds and/or jets → puncture the AGN disk → reduce accretion.
- → AGNs with medium large SMBH mass are ~unaffected.
- May unbind a large fraction of gas for AGNs with the smallest SMBHs – may explain dearth of high-Eddington ratio AGNs with SMBH mass $\lesssim 10^5 \mathrm{M}_\odot$.

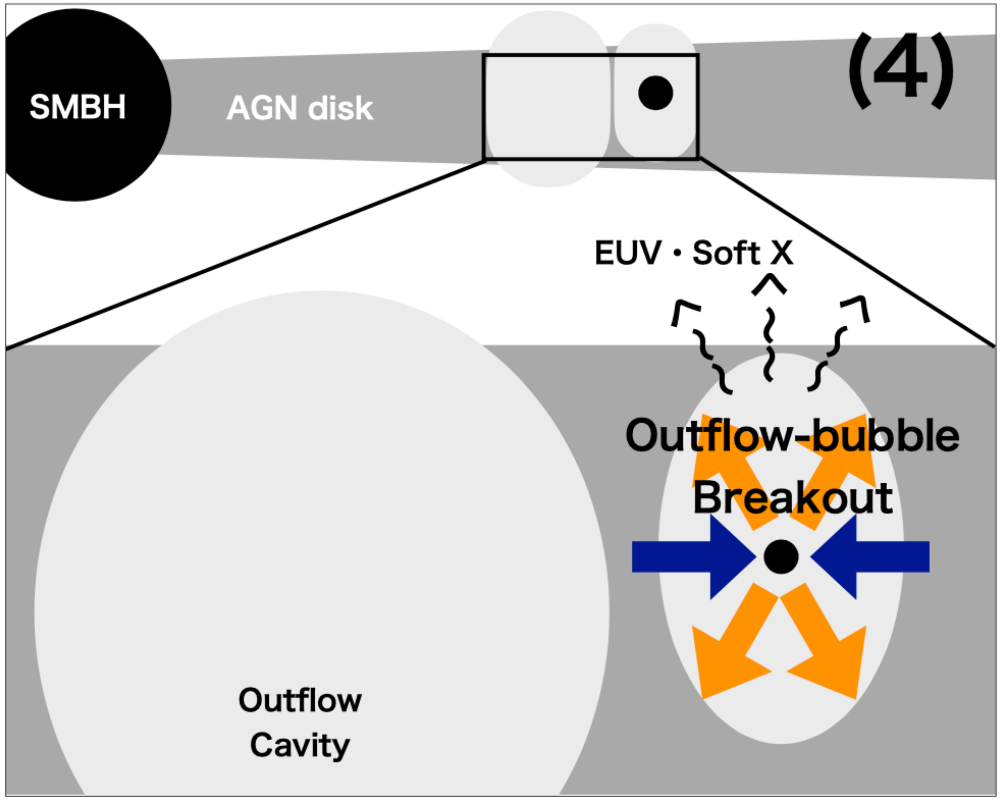


Tagawa+ 2021

Multi-messenger emission from black hole mergers in AGNs

Kimura+ 2021

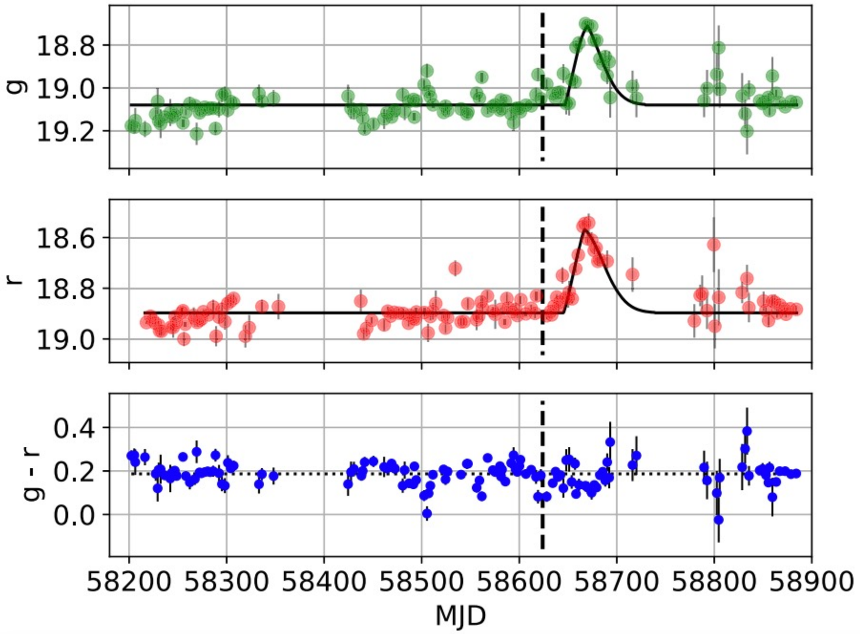


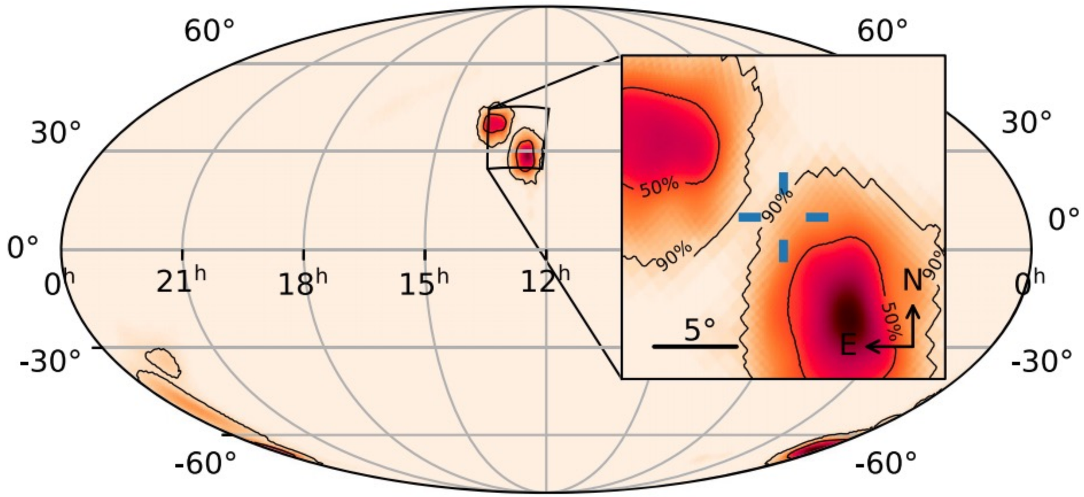


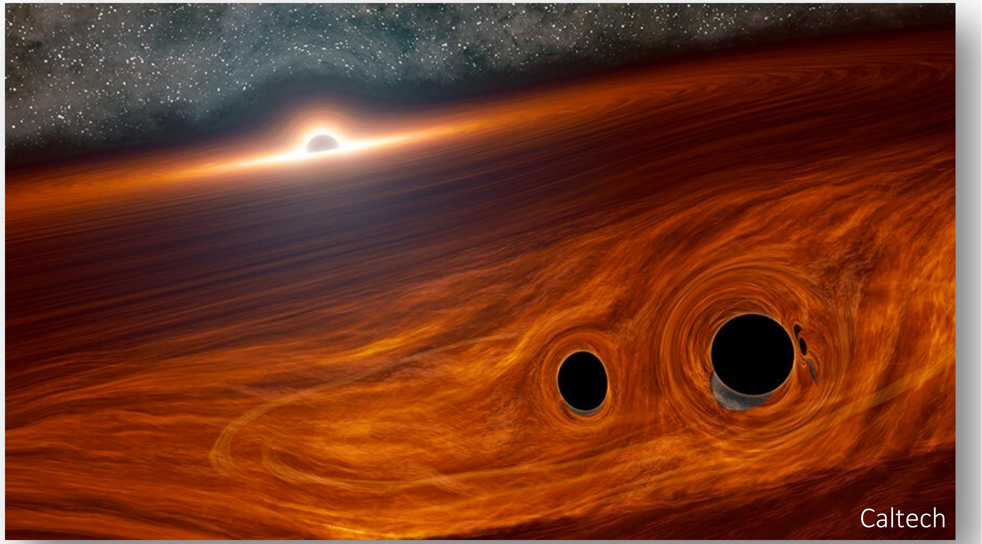
- Radiation driven outflows will balance accretion → **cavity + low accretion**
- Merger → GW recoil → remnant BH enters dense AGN disk → **high accretion** → soft X-ray (~500 Mpc with Swift/Chandra) + optical/IR (reprocessing)
- *Is inflow spherical/constant?*

Possible electromagnetic counterpart to GW190521

- Black hole merger EM follow-up search with ZTF (Graham+ PRL 2020).
- 2-months long transient in the wake of GW190521.
- EM signal consistent with AGN origin.
- Statistical significance depends on Bayesian priors of the GW signal, and it is difficult to fold in other evidence of the AGN origin of GW190521 → more of these would be welcome ;-)

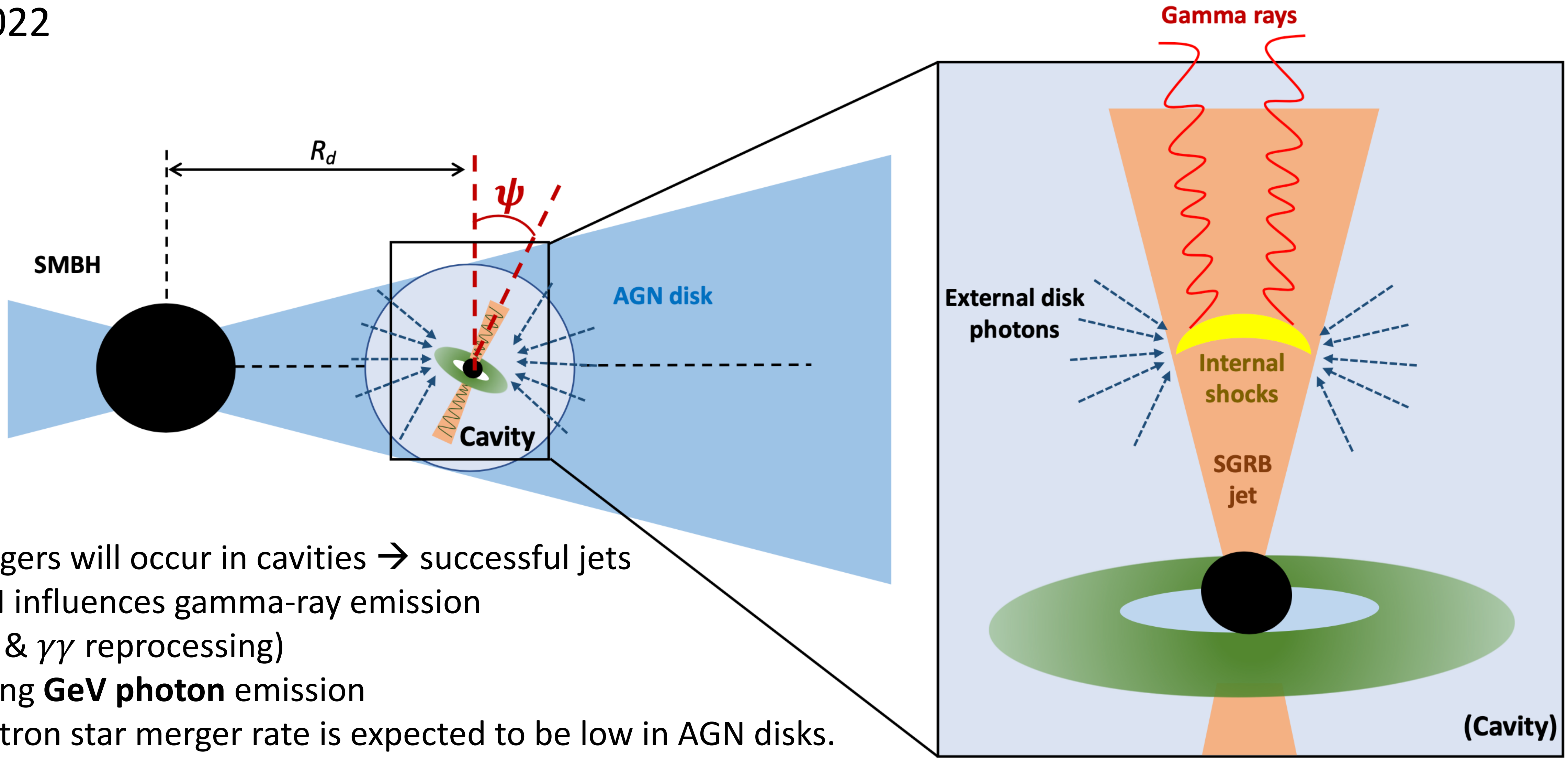






Neutron star mergers in AGN disks

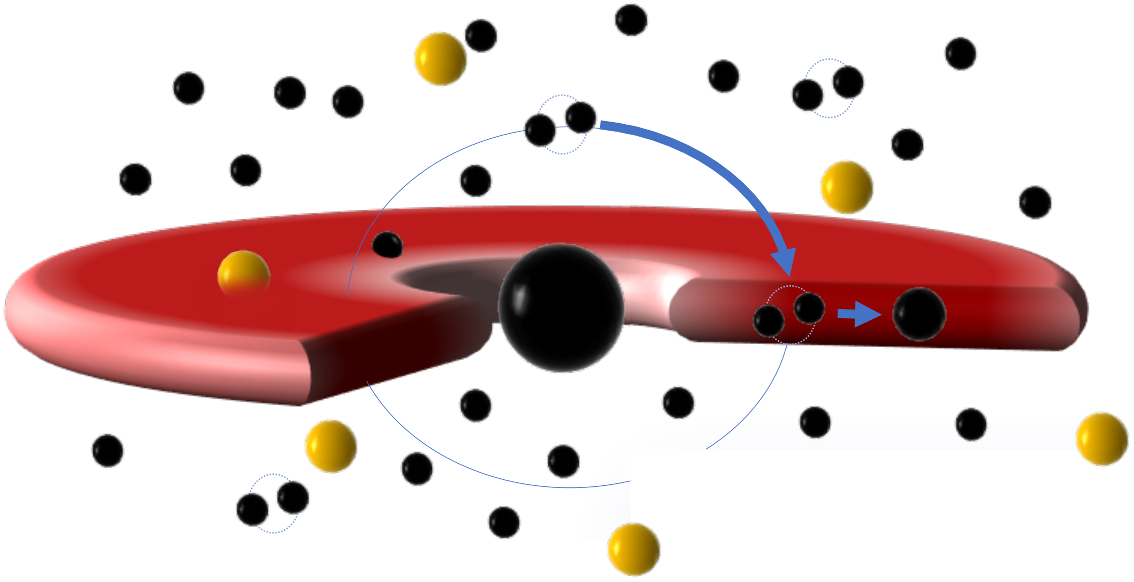
Yuan+ 2022



- Mergers will occur in cavities → successful jets
- AGN influences gamma-ray emission (EIC & $\gamma\gamma$ reprocessing)
- Strong **GeV photon** emission
- Neutron star merger rate is expected to be low in AGN disks.
- Same reprocessing works for black holes if they launch jets.

Micro Tidal Disruption Events in AGNs

- Stars and black holes align their orbits with AGN disk
- Gas capture → binaries
- Tidal disruption on stellar-mass black holes
- Possible bservational signatures:
  - Ultralong GRBs? (Perets+ 2016)
  - TDEs in AGNs.
    - ✓ TDE on SMBHs has higher rate.
    - ✓ Different emission profile?
    - ✓ SMBH mass $> 10^8 M_\odot$ - solar type stars are not disrupted by SMBH. Candidates:
      - ASASSN-15lh
      - ZTF19aailpwl



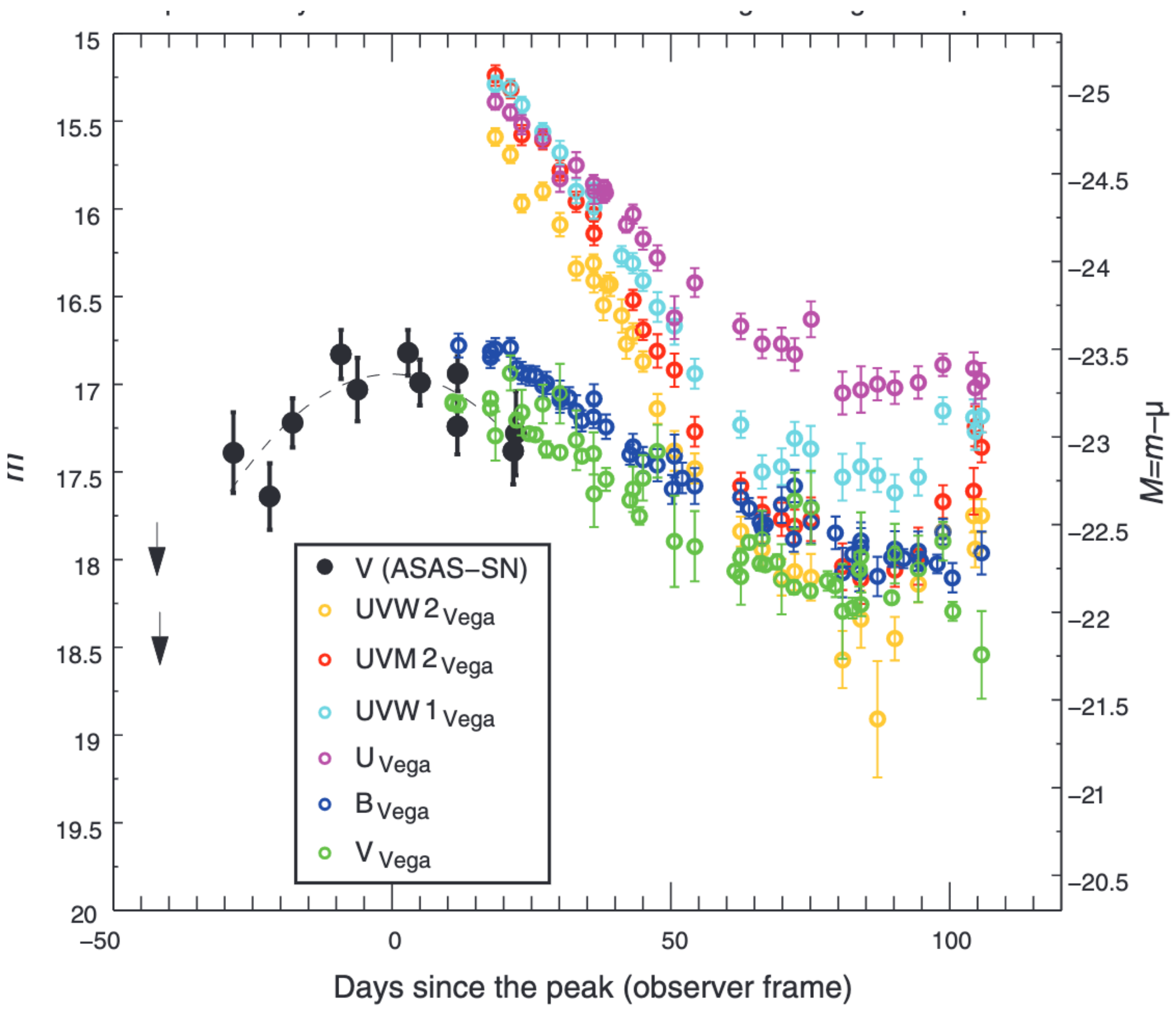
Expected Rate Density of Binary Mergers/Disruptions in AGNs

$\mathrm{Gpc}^{-3}\ \mathrm{yr}^{-1}$	Black Hole	Neutron Star	Star
Black hole	13	1	170
Neutron star		10^{-3}	0.14
Star			20

Yang+ ApJ Lett 2021

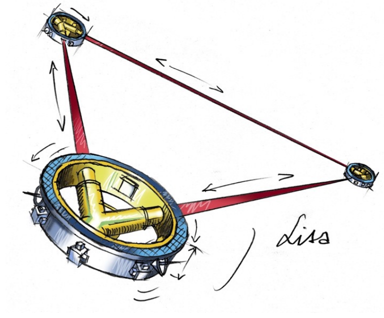
ASASSN-15lh

- z = 0.232 (Dong+ 2016).
- SMBH mass of $5^{+8}_{-3}{\times}10^8 M_\odot$ (Krühler+ 2018).
- Could still be solar type star and maximally spinning SMBH with $M_\bullet \sim 10^9 M_\odot$.
- Very high peak luminosity:
  $L_{peak} \sim 5{\times}10^{45} erg\ s^{-1}$
  higher than predicted for micro TDEs with solar type stars (e.g. Kremer+ 2021).
- Lack of hydrogen and helium features
  – Wolf-Rayet star?
  – Could also be a superluminous supernova? (Dong+ 2016)

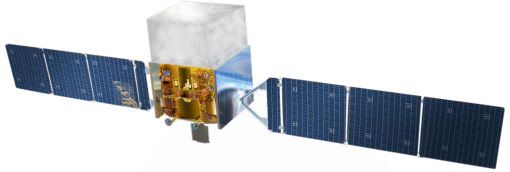


Dong+ 2016

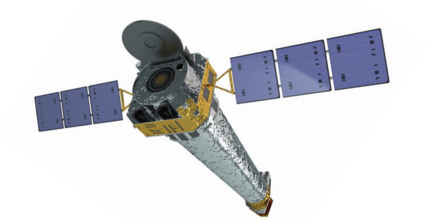
What time-domain/multi-wavelength observations are critical for answering related fundamental science questions?



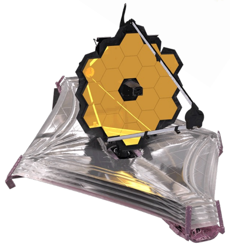
Gravitational waves – LIGO/Virgo/KAGRA's continued accumulation of mergers will be a key probe to what happens in AGN disks. LISA will probe growth of intermediate mass black holes and their fate.



Gamma-rays – jet launch by black holes before/after merger, ultra-long GRBs from micro TDEs; GeV emission due to AGN reprocessing.



X-ray – high accretion soon after black hole merger.



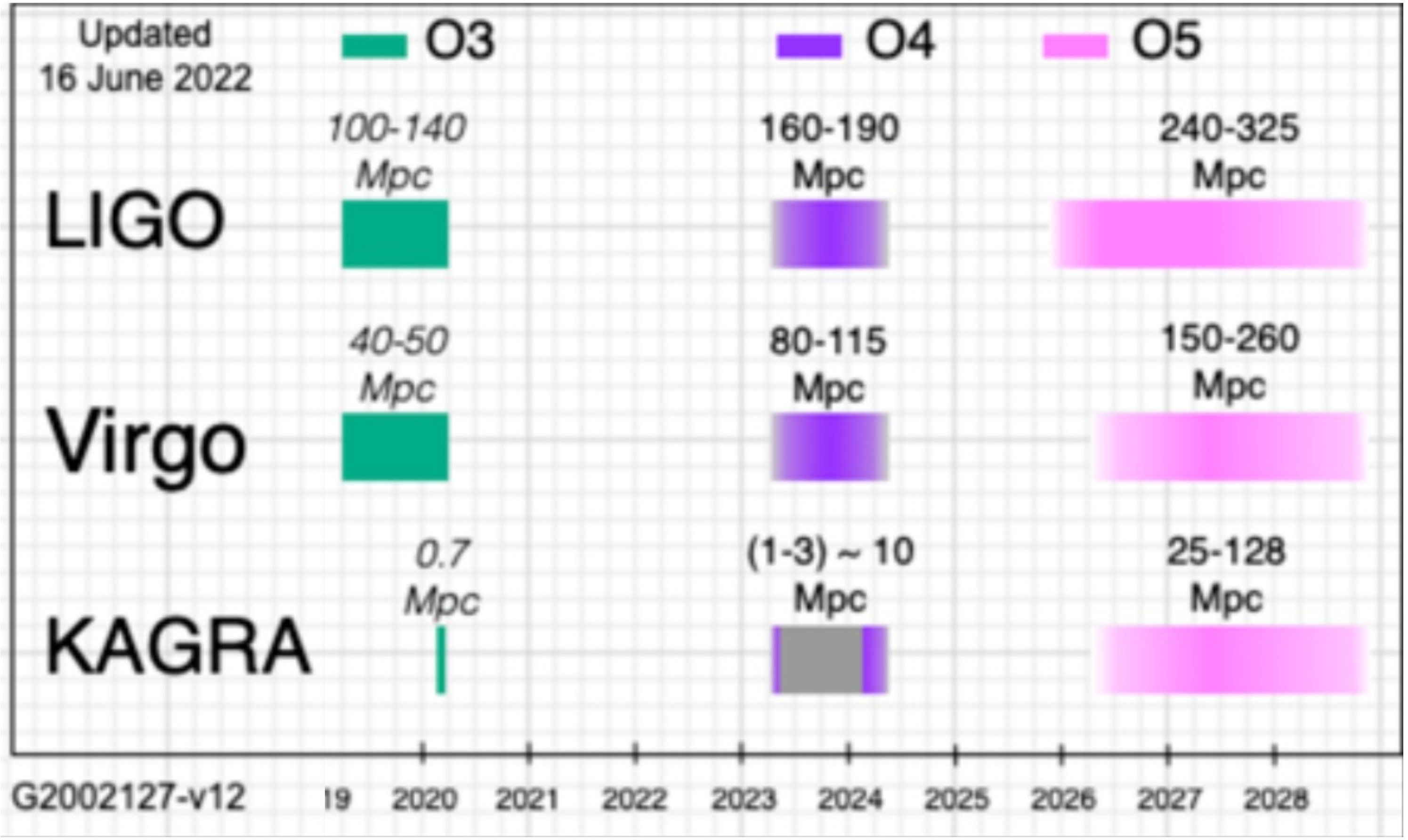
Optical – long-term, all-sky AGN variability/flare observations. Follow-up of detected black hole mergers.

Expected multi-messenger output and prospects for detection in the next 10 years?

Number of gravitational wave observations with LIGO/Virgo/KAGRA will expand significantly in next 10 years (LIGO-G2002127).

$\sim 20\%$ of black hole mergers might be from AGNs (Gayathr+ ApJ Lett. 2021).

Broad optical/EM follow-up of these events as well as the large number of discovered TDEs will probe what happens in AGNs.



What is needed?

Accretion processes by stellar objects in AGNs need to be better understood – hydrodynamical simulations.

Observations – critical to have all-sky gamma-ray observations (MeV-GeV).

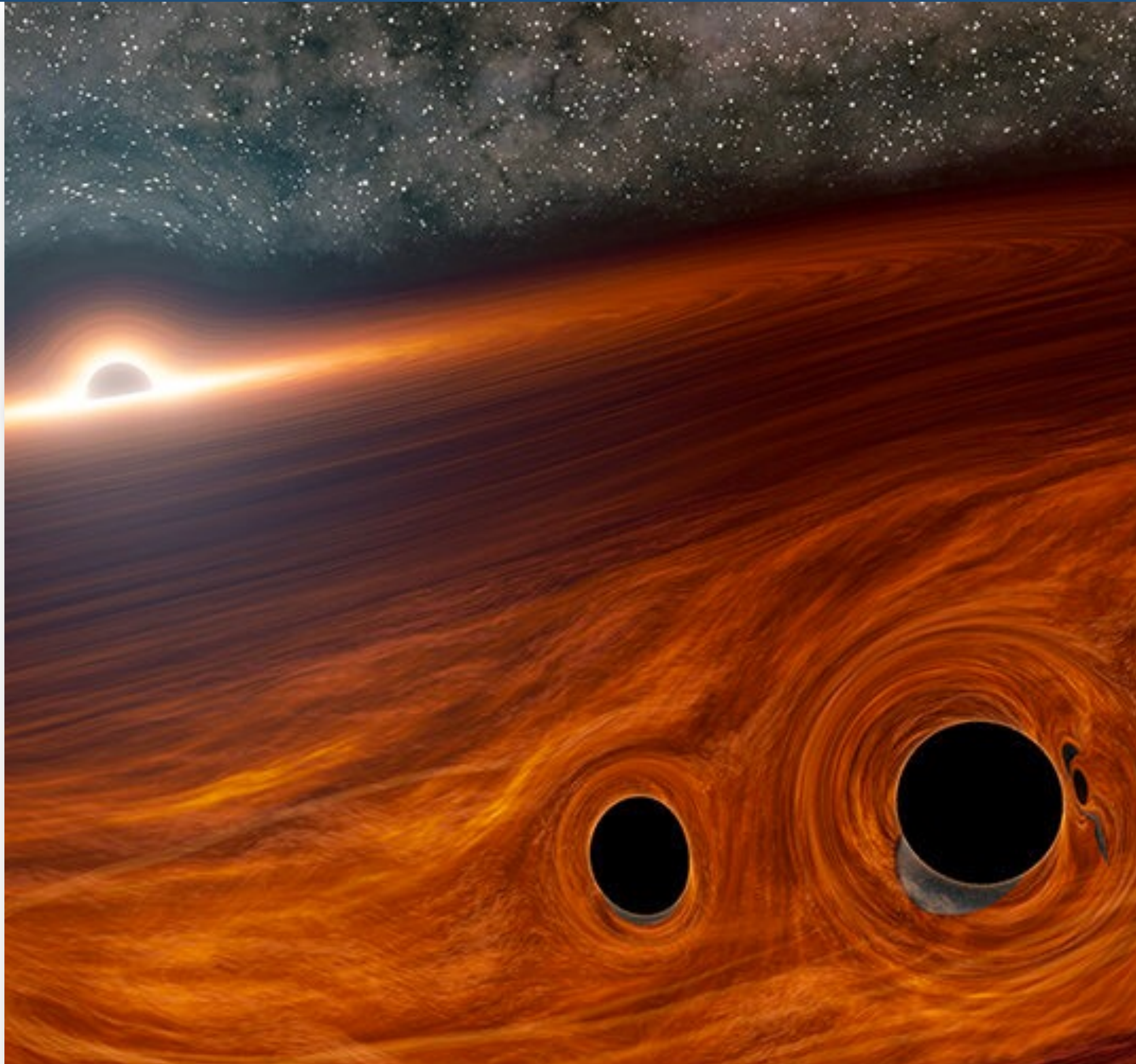
Observations – large FoV X-ray facility.

(Observations – Long-term optical monitoring.)

(Gravitational waves – LISA could slightly increase sensitivity to lower mass BHs.)

Summary

- AGN disks are expected to collect/produce stellar mass black holes, stars and neutron stars.
- These stellar objects in the disk interact with the disk and each other to produce transient, as well as possibly long-term, multi-messenger emission.
- We may have already detected black hole mergers and micro-TDEs occurring in AGN disks.
- Exciting multi-messenger possibilities for the next 10 years and beyond with improving and new facilities. All-sky long-term observations are needed across the EM band.
- Our understanding of stellar graveyards in AGN disks is still in its infancy. Lot of interesting open questions to study.



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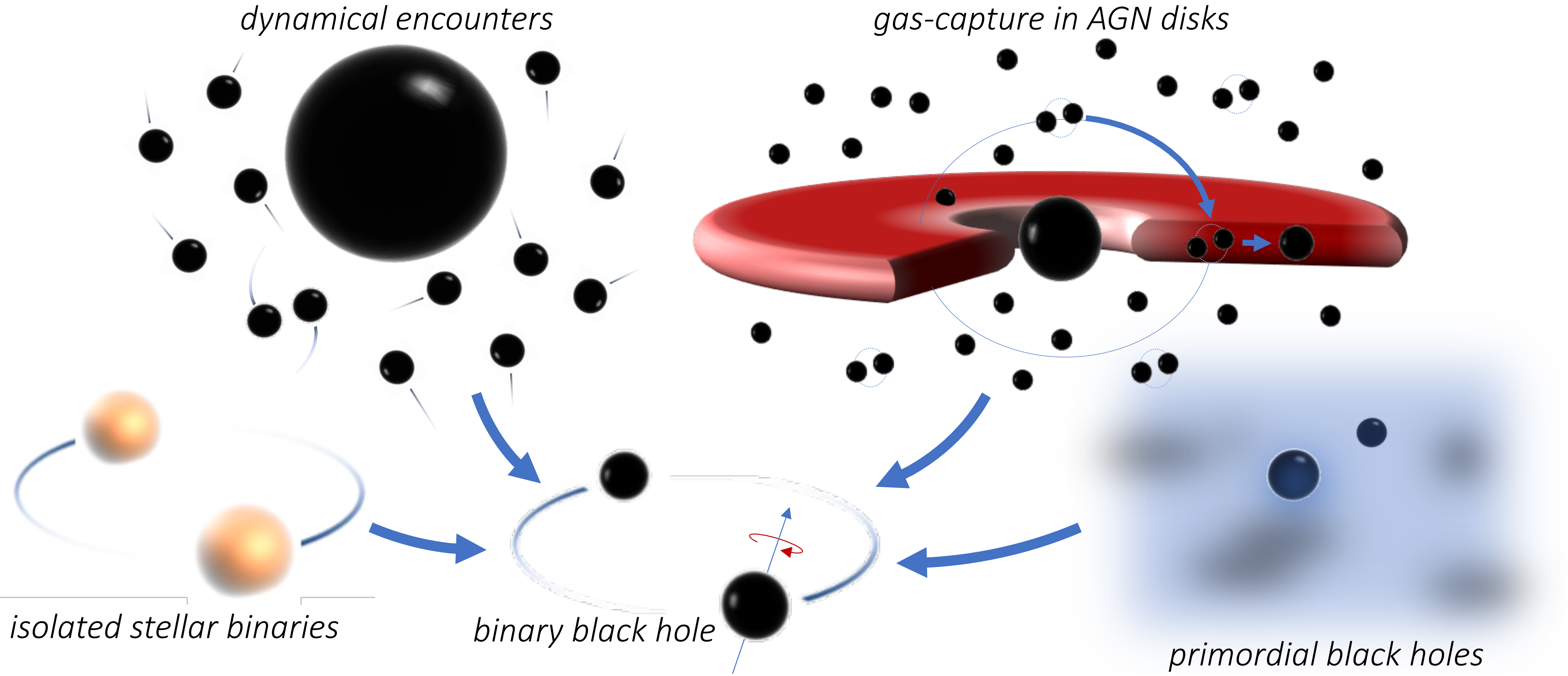
Possible origins of binary black holes



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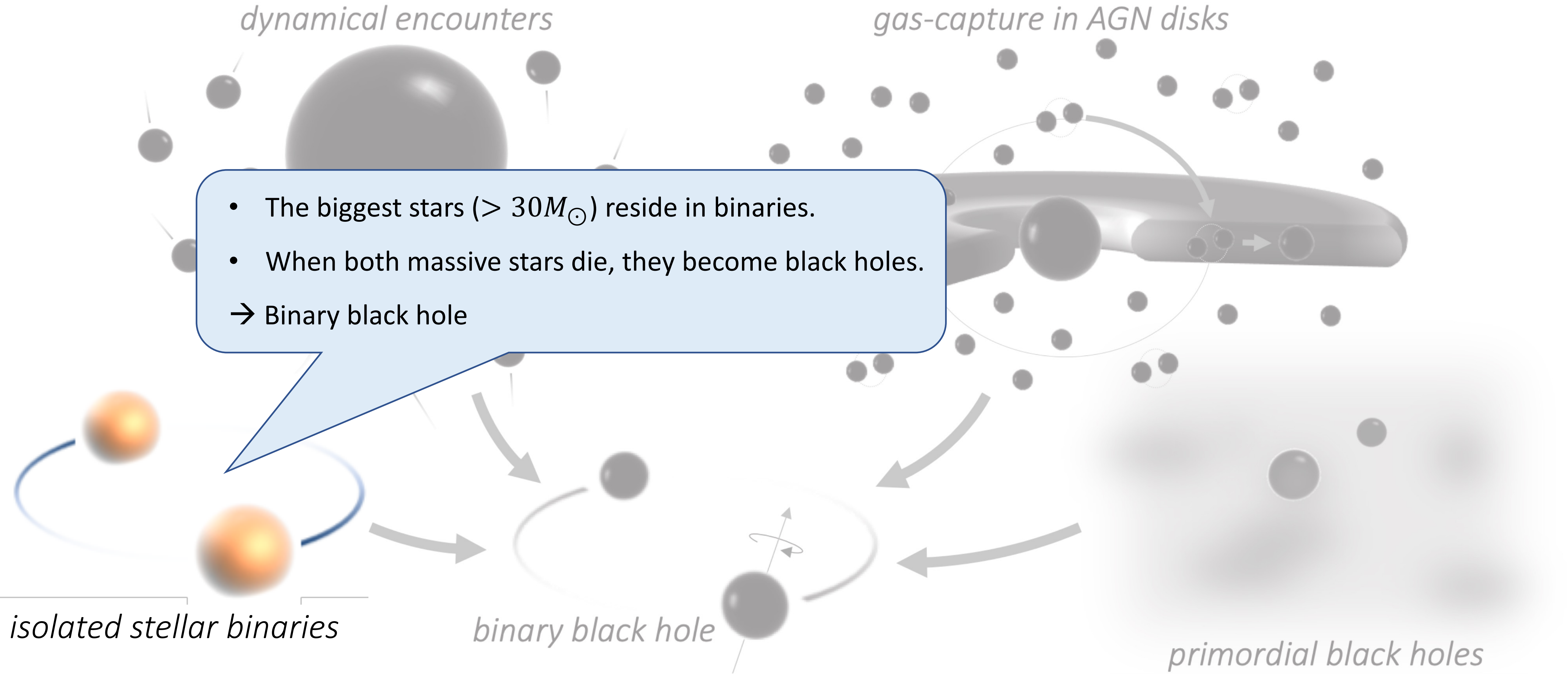
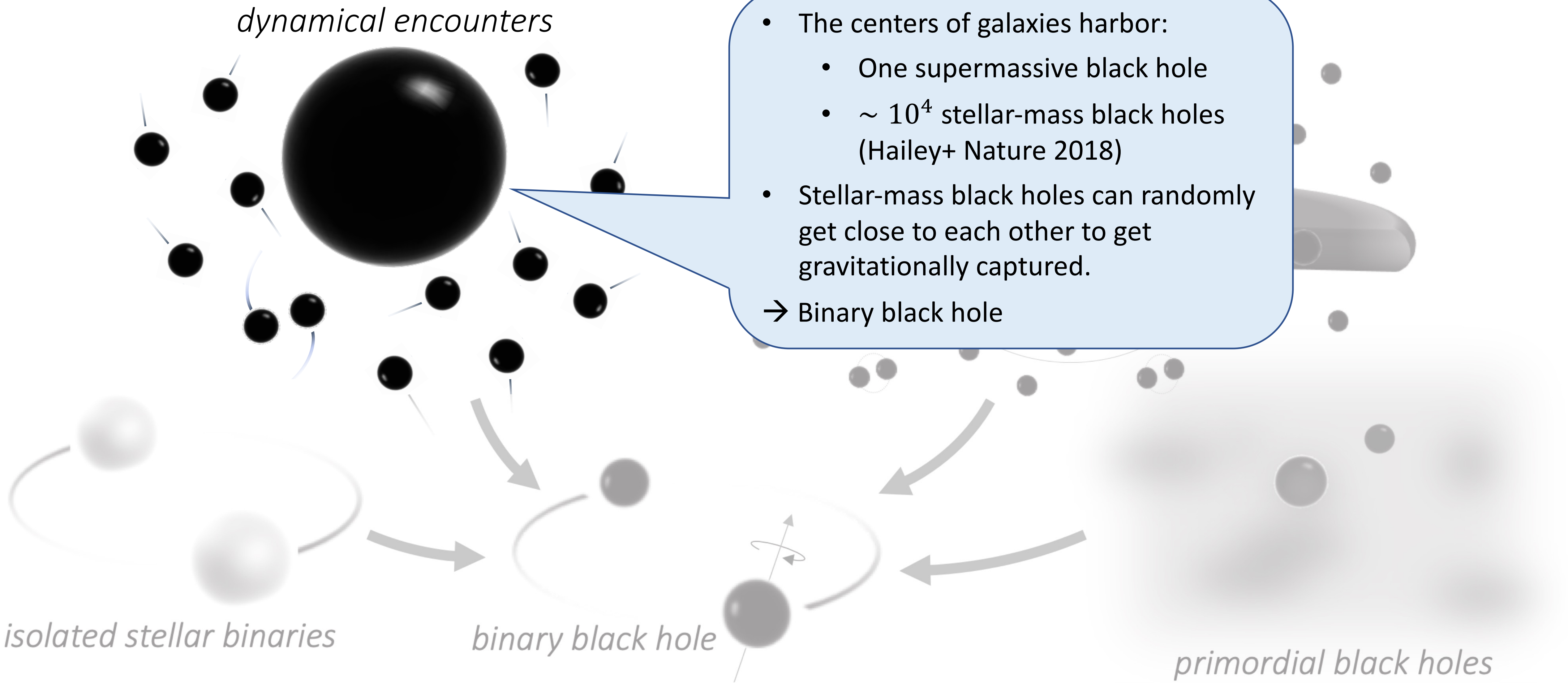


- The biggest stars ($> 30M_{\odot}$) reside in binaries.
- When both massive stars die, they become black holes.

→ Binary black hole

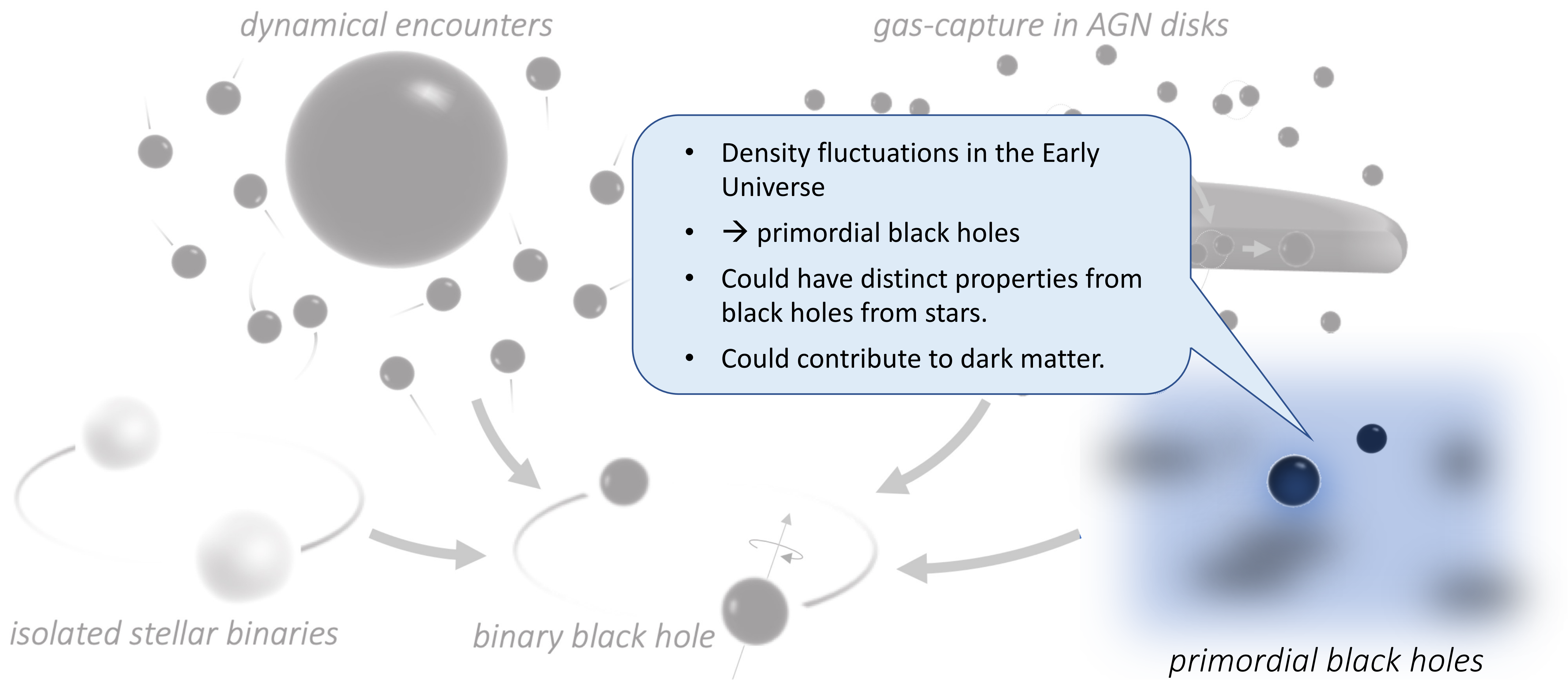
Possible origins of binary black holes



- The centers of galaxies harbor:
  - One supermassive black hole
  - $\sim 10^4$ stellar-mass black holes (Hailey+ Nature 2018)
- Stellar-mass black holes can randomly get close to each other to get gravitationally captured.

→ Binary black hole

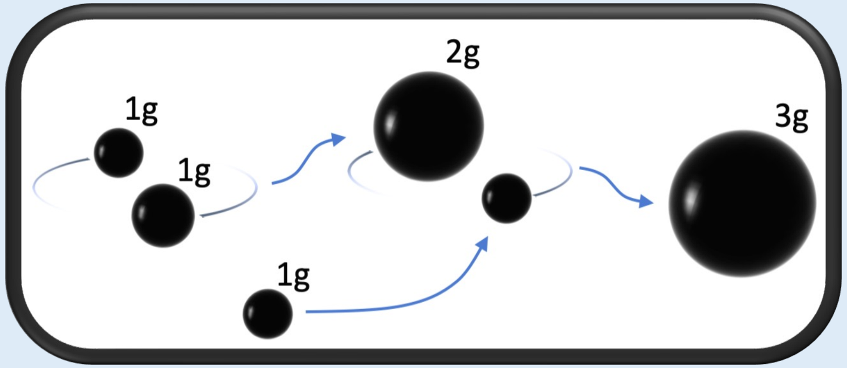
Possible origins of binary black holes

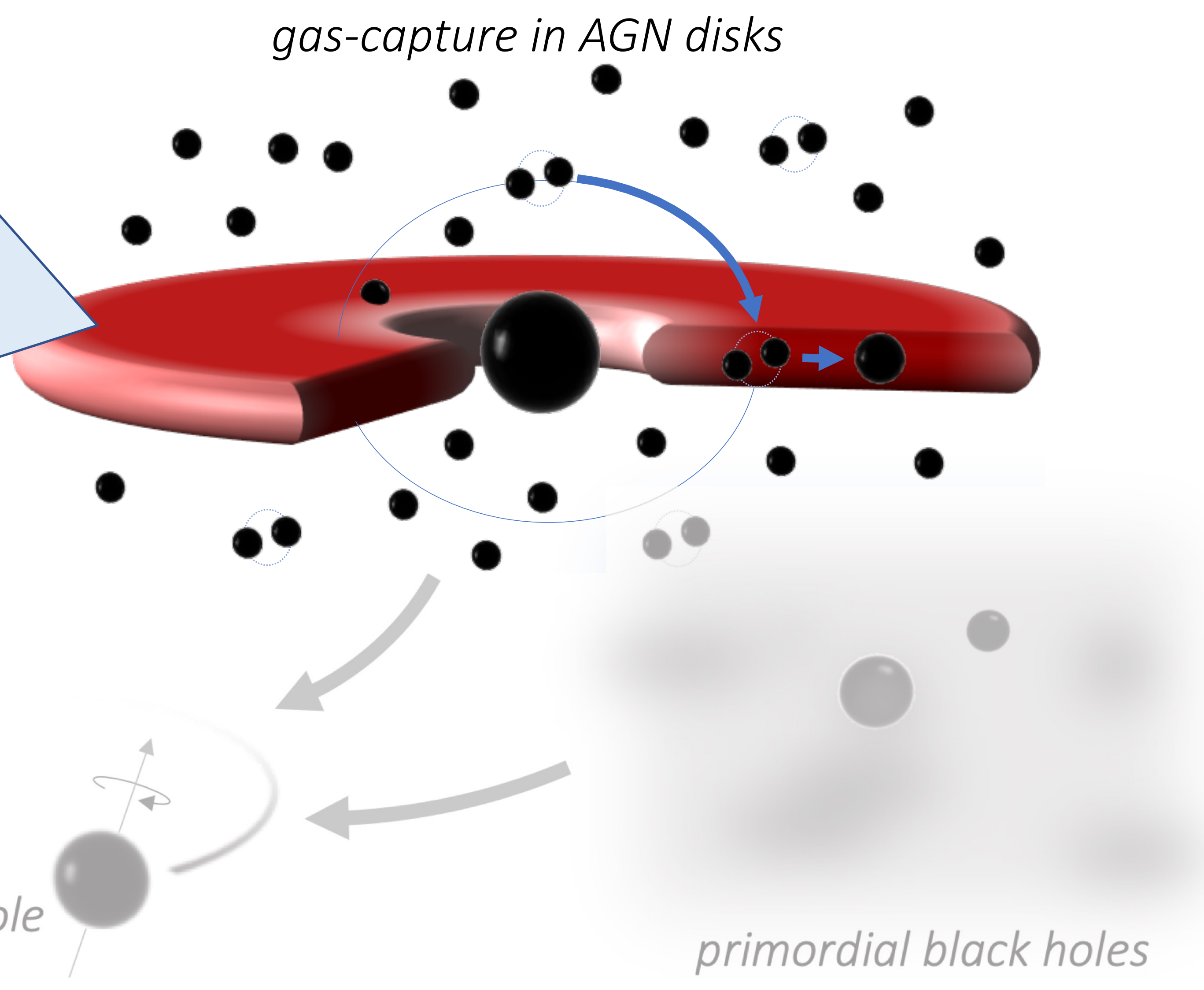


- Density fluctuations in the Early Universe
- → primordial black holes
- Could have distinct properties from black holes from stars.
- Could contribute to dark matter.

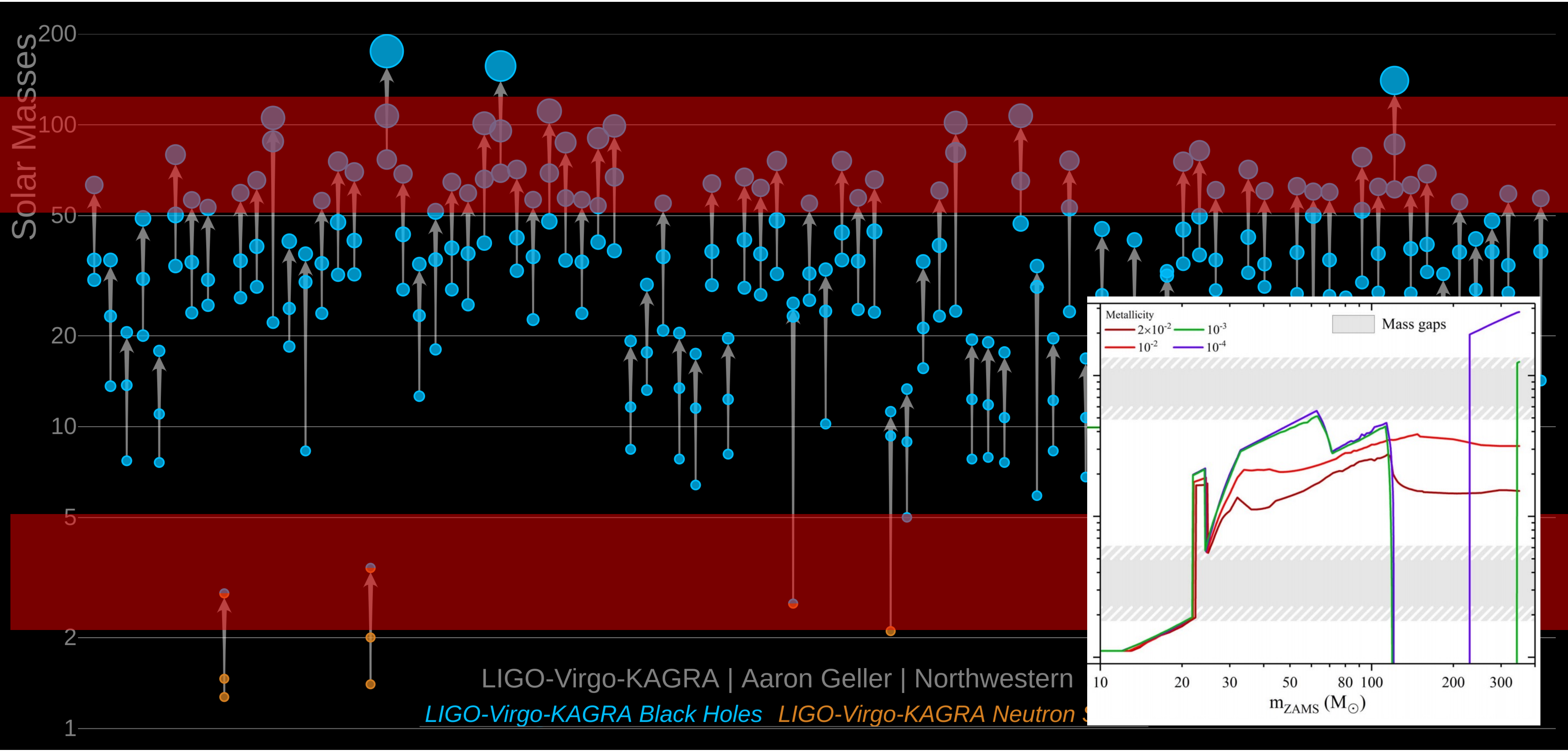
Possible origins of binary black holes

- Gas forms disk around SMBH.
- Disk drags black holes into the disk.
- Black holes migrate inward in disk (Ostriker 1983).
- Black holes inside merge.
  → **multi-messenger emission** due to surrounding gas? (Bartos+ 2017, McKernan+ 2019, Graham+ 2020)
- Black holes can **merge multiple times**, creating much heavier black holes (McKernan+ 2012, Yang+ 2019).





Special events



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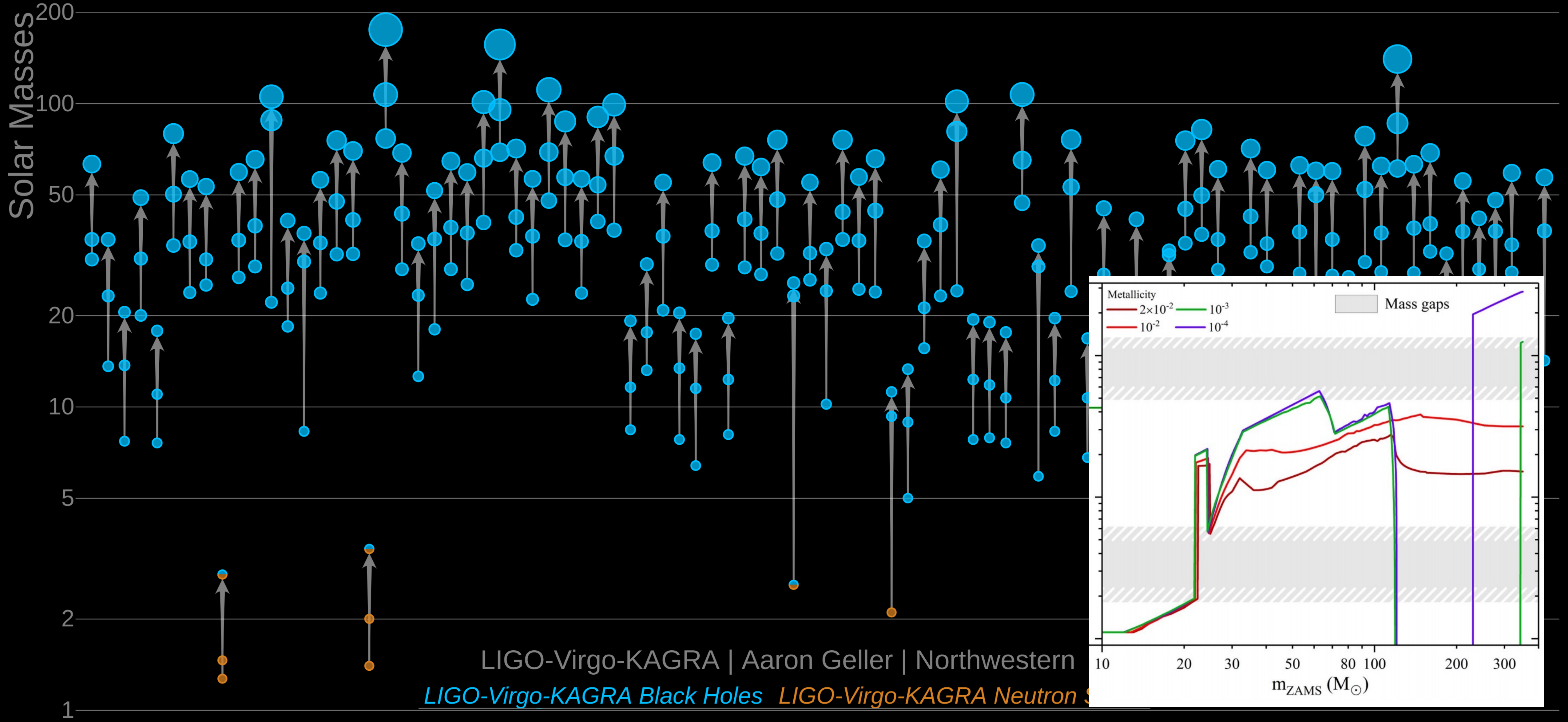

Special events